THE DISK MASS PROJECT

breaking the disk-halo degeneracy

Marc A.W. Verheijen[1*], Matthew A. Bershady[2], Rob A. Swaters[3],
David R. Andersen[4] and Kyle B. Westfall[2]
[1]*Kapteyn Astronomical Institute,* [2]*University of Wisconsin – Madison,*
[3]*University of Maryland,* [5]*NRC Herzberg Institute of Astrophysics*
[*]verheyen@astro.rug.nl

Abstract Little is known about the content and distribution of dark matter in spiral galaxies. To break the degeneracy in galaxy rotation curve decompositions, which allows a wide range of dark matter halo density profiles, an independent measure of the mass surface density of stellar disks is needed. Here, we present our ongoing Disk Mass project, using two custom-built Integral Field Units, to measure the vertical velocity dispersion of stars in ~40 spiral galaxies. This will provide a kinematic measurement of the stellar disk mass required to break the degeneracy, enabling us to determine the dark matter properties in spiral galaxies with unprecedented accuracy. Here we present preliminary results for three galaxies with different central disk surface brightness levels.

Keywords: galaxies: spiral — galaxies: fundamental parameters — galaxies: kinematics and dynamics — instrumentation: spectrographs

1. Motivation

A major roadblock in testing galaxy formation models is the disk-halo degeneracy: density profiles of dark matter halos as inferred from rotation curve decompositions depend critically on the adopted M/L of the disk component. An often used refuge to circumvent this degeneracy is the adoption of the maximum-disk hypothesis (van Albada & Sancisi 1986). However, this hypothesis remains unproven. Bell & De Jong (2001) showed that stellar population synthesis models yield plausible *relative* measurements of stellar M/L in old disks, but uncertainties in the IMF prevent an *absolute* measurement of stellar M/L from photometry. Another tool to determine the M/L, and specifically whether disks are maximal, is the Tully-Fisher relation, e.g. by looking for offsets between barred vs. un-barred galaxies, but this too is only a relative measurement. Evidently, none of these methods are suited to break the degen-

eracy, and without an independent measurement of the M/L of the stellar disk, it is not possible to determine the structural properties of dark matter halos from rotation curve decompositions.

A direct and absolute measurement of the M/L can be derived from the vertical component σ_z of the stellar velocity dispersion. For a locally isothermal disk, $\sigma_z = \sqrt{\pi G(M/L)\mu z_o}$, with μ the surface brightness, and z_0 the disk scale height. The latter is statistically well-determined from studies of edge-on galaxies (de Grijs & van der Kruit 1996, Kregel et al 2002). Thus, σ_z provides a direct, kinematic estimate of the M/L of a galaxy disk and can break the disk-halo degeneracy.

This approach has been attempted before with long-slit spectroscopy on significantly inclined galaxies. For example, Bottema (1997) concluded for a sample of 12 galaxies that, on average, the stellar disk contributes at maximum some 63% to the amplitude of the rotation curve. These observations, however, barely reached 1.5 disk scale-lengths, required broad radial binning, and because of the high inclinations, the measured velocity dispersions required large and uncertain corrections for the tangential (σ_ϕ) and radial (σ_r) components of an assumed velocity dispersion ellipsoid.

2. The Disk Mass Project

Measuring σ_z in kinematically cold stellar disks requires spectroscopy at moderately high resolution (R≈10^4) of extended light at relatively low surface brightness levels ($\mu_B \approx 24$ mag/arcsec^2). Clearly, measurements of σ_z have been severely hampered by the limited signal-to-noise of the observations to date, as well as the small samples of galaxies studied so far.

With the advent of Integral Field Unit (IFU) spectroscopy, the observational situation can be dramatically improved, and significant progress in determining the mass surface densities of stellar disks can now be made. The main advantage of IFU spectroscopy over traditional long-slit studies lies in the fact that IFUs are capable to collect light from a much larger solid angle and that many IFU spectra can be combined to increase the signal-to-noise.

Capitalizing on this aspect of IFU spectroscopy, we have initiated our long-term Disk Mass project. The main goal is to measure σ_z as a function of radius out to 2.5 disk scale lengths in ∼40 undisturbed, nearly face-on spiral galaxies with a wide range of global properties like total luminosity, surface brightness, colour, and morphology. To achieve this, we have constructed two special-purpose wide-field fiber-based IFUs, and adopted a two-phased observational strategy extending over a 3-4 year period.

Phase A aims at collecting Hα velocity fields for a parent sample of nearly phase-on spiral galaxies. From the UGC, we selected disk galaxies at $|b| \geq 25^\circ$ to minimize Galactic extinction, with diameters between $1'$ and $1.5'$ to match

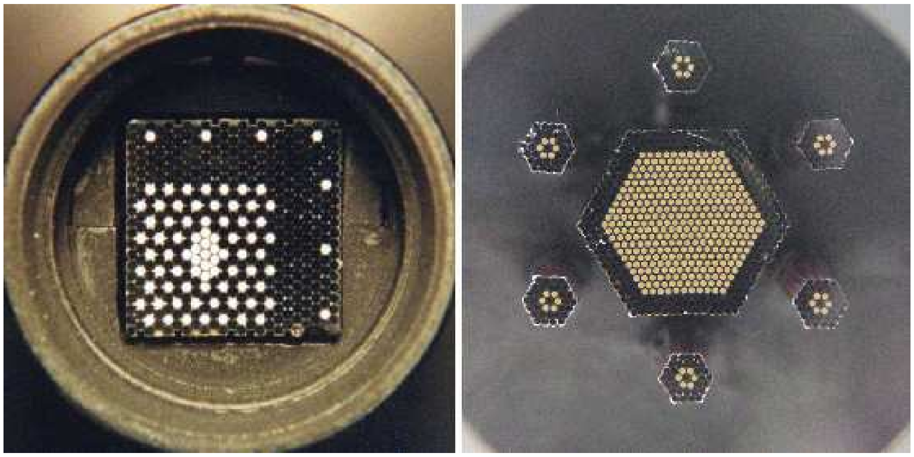

Figure 1. Two custom-built fiber-based wide-field IFUs. Active fibers are back-illuminated. Dark fibers terminate shortly behind the focal plane and serve as buffer for stress relief and to edge-protect the active fibers while polishing the fiber head.**Left:** focal plane layout of the fibers in the SparsePak IFU: the grid is filled with 3 pointings. **Right:** focal plane layout of the fibers in the P-Pak IFU. Sky fibers are located in 6 mini-IFUs surrounding the main fiber head.

them to the large field-of-view of our IFUs, and with optical axis ratios of b/a$>$0.85 to ensure a nearly face-on orientation. This yielded a total sample of 470 galaxies from which we removed the strongly barred and interacting galaxies, and randomly picked galaxies to observe.

Subsequently, the regularity of the gas kinematics is evaluated from the Hα velocity fields. The main purpose is to identify kinematically disturbed disks which are likely to violate the assumption of local isothermal equilibrium, which is required when relating $\sigma_{\rm z}$ and disk scale height to the mass surface density of the disk. Furthermore, Andersen & Bershady (2003) have demonstrated that accurate inclinations and rotation curves can be derived for nearly face-on disks, provided a regular and symmetric Hα velocity field of high signal-to-noise. The parent sample will be expanded until 40 galaxies with regular gas kinematics have been identified.

Phase B of our project aims at measuring $\sigma_{\rm z}$ in the stellar disks of the sub-sample of 40 galaxies with regular gas kinematics. Velocity dispersions are determined from the broadening of the absorption lines in the blue part of the spectrum around 515 nm, containing absorption lines of the MgIb triplet and many Fe lines. For a selected number of galaxies, $\sigma_{\rm z}$ is also measured from the broadened CaII triplet absorption lines around 860 nm.

Apart from these spectroscopic observations with our IFUs, all galaxies in the parent sample will be imaged in the U,B,V,R,I and J,H,K passbands. All

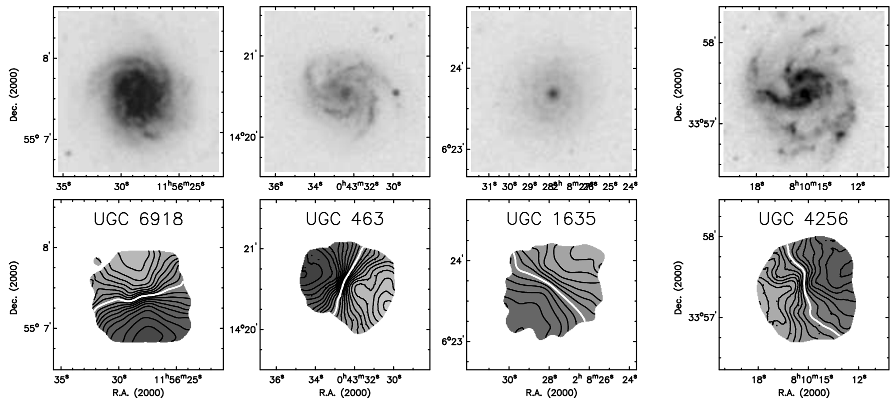

Figure 2. Examples of galaxies in the parent sample. **Upper row:** optical images at the same grayscale levels. **Bottom row:** Hα velocity fields obtained with SparsePak. The three galaxies on the left, with different central disk surface brightness levels, are suitable for follow-up observations of their stellar kinematics which are presented in Figure 3. UGC 4256 is an example of a galaxy which is too irregular, as is the case for most galaxies in our parent sample.

galaxies in the subsample will be imaged in neutral hydrogen to determine the contribution from the cold gas to the total surface mass density of the disks.

3. Two custom-built Integral Field Units

As mentioned above, measuring σ_z requires spectroscopy at moderately high spectral resolution of diffuse low surface brightness light. To achieve this, we have built two special-purpose wide-field IFUs consisting of large aperture fibers which carry light from a focal plane to the pseudo-slit of a pre-existing spectrograph. The diameter of the fibers is maximized while providing a spectral resolution of no less than R≈8000. The maximum number of fibers is then determined by the length of the spectrograph slit, while the layout in the focal plane is designed to span more than an arcminute on the sky. Obviously, the penalty paid for large aperture fibers is a limited angular resolution, but this is of secondary importance for our Disk Mass project.

SparsePak, built at the University of Wisconsin in Madison, contains 75 science and 7 sky fibers, each 4.7 arcsec in diameter (Fig. 1). The 25m long fibers pipe light from a $71'' \times 72''$ field-of-view (fov) at the F/6 imaging port of the 3.6m WIYN telescope at Kitt Peak to its Bench Spectrograph. SparsePak is described in detail by Bershady et al (2004, 2005).

P-Pak, built at the AIP in Potsdam, contains 331 science and 36 sky fibers, each 2.7 arcsec in diameter (Fig. 1). The 3m long fibers carry light from a $64'' \times 74''$ hexagonal fov at the focal plane behind a F/3.5 focal reducer lens on

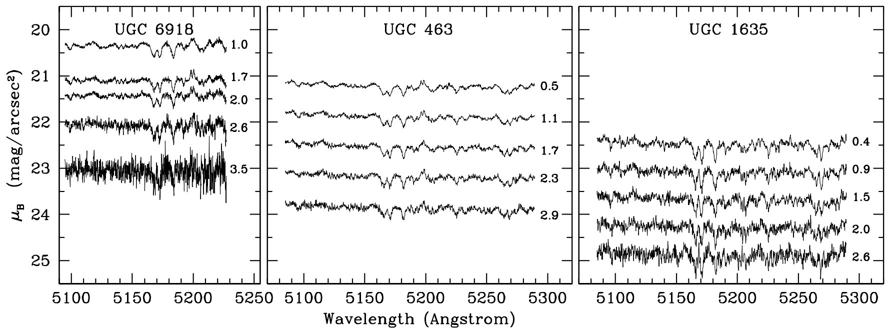

Figure 3. Azimuthally averaged absorption line spectra at 5 radial bins for 3 galaxies with different central surface brightness. Each spectrum is plotted at the corresponding surface brightness level. At the right of each spectrum, the number of disk scale lengths for the radial bin is indicated. U6918 was observed for $3\times45^{\rm min}$ with SparsePak at R=11,750. U463 and U1635 were observed for $5\times60^{\rm min}$ with P-Pak at R=7,800. The number of averaged spectra at each radius is 6, 8, 12, 18, and 18 for SparsePak, and 18, 42, 66, 90, and 114 for P-Pak.

the 3.5m Calar Alto telescope, to the collimator lens of the Cassegrain mounted PMAS spectrograph (Verheijen et al 2004, Kelz et al 2005). Fifteen additional fibers allow for an accurate simultaneous wavelength calibration.

4. Current status

Phase A is effectively complete. From analyzing the gas kinematics (Fig. 2), it became clear that only about 1 in 3 galaxies have sufficiently regular gas kinematics to succesfully fit a tilted-ring model to the Hα velocity field, allowing us to measure the shape and amplitude of the inner rotation curves from which to total mass (dark plus luminous) of the inner galaxy follows. Hence, a parent sample of 130 galaxies has been constructed from which a subsample of 40 regular galaxies can be selected.

We have started Phase B in the fall of 2004 and observed the stellar kinematics in the MgIb region with P-Pak for 11 galaxies. With SparsePak we have observed the MgIb kinematics for 8 and CaII kinematics of 7 galaxies. With both IFUs we have built up an extensive library of spectroscopic template stars covering a range of spectral types, metallicities and log(g).

5. First results

Figure 3 shows, for 3 galaxies with different disk central surface brightness levels, the azimuthally averaged stellar absorption line spectra in the MgIb region of the spectra for five radial bins. Using the stellar template spectra, we have measured σ_z as a function of radius, assuming a Gaussian broadening

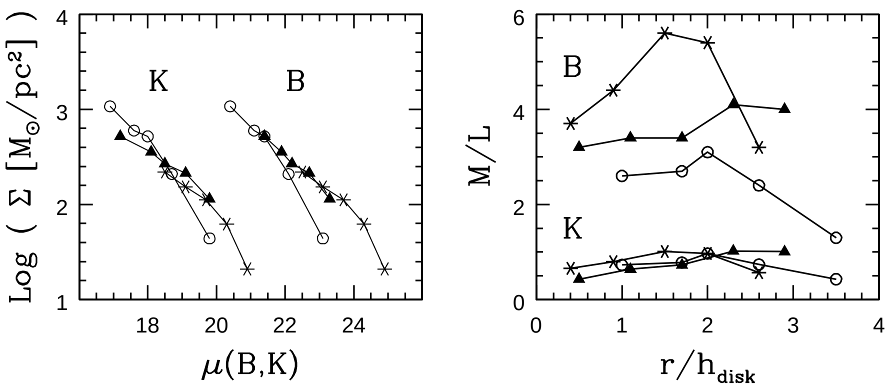

Figure 4. **Left:** Mass surface density as function of local B- and K-band surface brightness. **Right:** Mass-to-light ratios in the B- and K-band as a function of radius. Circles: U6918, triangles: U463, asteriks: U1635. Lacking K-band photometry for U1635 forced us to adopt a B−K colour constant with radius.

function. Figure 4 shows the derived mass surface densities and mass-to-light ratios. Although we are dealing with three entirely different galaxies, the K-band M/L is quite similar for these galaxies while the B-band M/L seems to increase systematically with lower central disk surface brightness.

Acknowledgments

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